

Testing the Standard Model with $B_s^0 \rightarrow K^+ K^-$ Decays

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In the limit of flavor SU(3) symmetry, the amplitudes for $B_d^0 \rightarrow \pi^+ \pi^-$ and $B_s^0 \rightarrow K^+ K^-$ are related to one another. Taking the values of the weak phases β and γ from independent measurements, the ratio $R_d^s \equiv BR(B_s^0 \rightarrow K^+ K^-)/BR(B_d^0 \rightarrow \pi^+ \pi^-)$ and the two $B_d^0 \rightarrow \pi^+ \pi^-$ CP asymmetries \mathcal{A}_{dir} and \mathcal{A}_{mix} depend on only two quantities. By measuring these three observables, one can test for the presence of physics beyond the standard model. In this paper, using present data, and including theoretical uncertainties due to SU(3) breaking, we perform such an analysis. The experimental errors are still very large, but with improved measurements from Babar, Belle and CDF this will be a useful method to search for new physics.

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At present, we do not have reliable theoretical computations of individual B decay rates. For example, calculations within QCD factorization [1] predict $BR(B^0 \rightarrow \pi^+ \pi^-)$ to be larger, and $BR(B^0 \rightarrow \pi^0 \pi^0)$ smaller, than what is found experimentally [2]. This may imply the presence of physics beyond the standard model (SM), or there might be a problem with QCD factorization. Indeed, in Ref. [3], it is argued that new physics is unnecessary. Rather, large nonfactorizable effects can account for the experimental branching ratios. On the other hand, calculations within soft-collinear effective theory yield $B \rightarrow \pi\pi$ branching ratios which are consistent with the data [4] without invoking nonfactorizable effects of the type discussed in Ref. [3].

This brief discussion underscores the fact that the calculation of rates for individual B decays is very difficult. If one wishes to search for new physics, it is better to look at ratios of decay rates. If, due to some symmetry, the ratio of two rates is exactly predicted in the SM, then any deviation from this prediction would be a clear signal of physics beyond the SM.

It is therefore natural to try to relate $B^0 \rightarrow \pi^+ \pi^-$ to another decay using flavor SU(3) symmetry. The obvious partner decay is $B^0 \rightarrow K^+ \pi^-$ [5]. In terms of diagrams, the amplitudes for these two processes are [6]

$$\begin{aligned} A(B_d^0 \rightarrow \pi^+ \pi^-) &= -T - P - E - PA - \frac{2}{3}P_{EW}^C, \\ A(B_d^0 \rightarrow K^+ \pi^-) &= -T' - P' - \frac{2}{3}P_{EW}^C. \end{aligned} \quad (1)$$

In the above, the amplitudes are written in terms of a color-favored tree amplitude T , a gluonic penguin amplitude P , an exchange amplitude E , a penguin annihilation amplitude PA , and a color-suppressed electroweak penguin amplitude P_{EW}^C . For $\bar{b} \rightarrow \bar{d}u\bar{u}$ ($B^0 \rightarrow \pi^+ \pi^-$) and $\bar{b} \rightarrow \bar{s}u\bar{u}$ ($B^0 \rightarrow K^+ \pi^-$), we write the diagrams with

no primes and primes, respectively. If one assumes that the spectator quark plays no role in the decay, then the nonfactorizable contributions E and PA are negligible. In this case, the various contributions to the two amplitudes are equal, apart from elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. However, the neglect of E and PA is problematic. If nonfactorizable effects do indeed play an important role in $B^0 \rightarrow \pi^+ \pi^-$ [3], then the SU(3) relations between the $B^0 \rightarrow \pi^+ \pi^-$ and $B^0 \rightarrow K^+ \pi^-$ amplitudes are invalidated.

Naive estimates of P and PA put them at $\lesssim 5\%$ of the dominant contributions [6]. However, their size is really an experimental question. Some decays (e.g. $B_d^0 \rightarrow D_s^+ D_s^-$, $B_d^0 \rightarrow K^+ K^-$, $B_s^0 \rightarrow \pi^+ \pi^-$, etc.) proceed mainly through exchange-type interactions involving the spectator quark. The measurement of these rates will provide an estimate of the size of exchange-type contributions.

Because of the uncertainty about nonfactorizable effects, a better partner decay is $B_s^0 \rightarrow K^+ K^-$. Its amplitude is

$$A(B_s^0 \rightarrow K^+ K^-) = -T' - P' - E' - PA' - \frac{2}{3}P_{EW}^{\prime C}. \quad (2)$$

Thus, even including nonfactorizable effects, the amplitude for this decay is related by SU(3) (U-spin) to that for $B_d^0 \rightarrow \pi^+ \pi^-$ [7]. It is therefore possible to relate observables measured in one decay to those in the other decay. The only theoretical uncertainty is the breaking of SU(3) [7, 8].

The idea of relating the amplitudes of $B_d^0 \rightarrow \pi^+ \pi^-$ and $B_s^0 \rightarrow K^+ K^-$ via SU(3) is not new. It has been used in Refs. [3, 7, 9, 10, 11] to relate observables in the two decays. In particular, the CP asymmetries in $B_s^0(t) \rightarrow K^+ K^-$ can be written in terms of the same parameters that appear in the CP asymmetries for

$B_d^0(t) \rightarrow \pi^+\pi^-$ (up to SU(3)-breaking effects [7, 8]). In the present paper we note that the branching ratio (BR) for $B_s^0 \rightarrow K^+K^-$ can be written in terms of the observables found in $B_d^0(t) \rightarrow \pi^+\pi^-$. Thus, the measurements of the BR and CP asymmetries in $B_d^0(t) \rightarrow \pi^+\pi^-$ and the BR for $B_s^0 \rightarrow K^+K^-$ provide a straightforward consistency check of the SM. Furthermore, all four of these quantities have already been measured so that it is possible to apply this test now. (Unfortunately, as we will see, because of the large experimental errors, no firm conclusions can be drawn at present.)

Within the SM, the decay $B_d^0 \rightarrow \pi^+\pi^-$ receives charged-current contributions, proportional to $V_{ub}^*V_{ud}$, and penguin contributions $V_{ub}^*V_{ud}P_u + V_{cb}^*V_{cd}P_c + V_{tb}^*V_{td}P_t$. (The charged-current term includes the T and E diagrams of Eq. (1). Similarly, the penguin term includes P , PA and P_{EW}^C .) Using CKM unitarity to eliminate P_t , the penguin contributions become $V_{ub}^*V_{ud}(P_u - P_t) + V_{cb}^*V_{cd}(P_c - P_t)$. The amplitude for $B_d^0 \rightarrow \pi^+\pi^-$ can then be written [7]

$$A(B_d^0 \rightarrow \pi^+\pi^-) = V_{ub}^*V_{ud}(A_{CC}^u + A_{\text{pen}}^{ut}) + V_{cb}^*V_{cd}A_{\text{pen}}^{ct} \\ = \mathcal{C}(e^{i\gamma} - de^{i\theta}), \quad (3)$$

where $A_{\text{pen}}^{it} \equiv P_i - P_t$ ($i = u, c$), γ is a CP phase [12], and

$$\mathcal{C} \equiv |V_{ub}^*V_{ud}|(A_{CC}^u + A_{\text{pen}}^{ut}), \\ de^{i\theta} \equiv \frac{1}{R_b} \left(\frac{A_{\text{pen}}^{ct}}{A_{CC}^u + A_{\text{pen}}^{ut}} \right), \quad (4)$$

with $R_b = |(V_{ub}^*V_{ud})/(V_{cb}^*V_{cd})|$. In the above, θ is the relative strong phase between A_{pen}^{ct} and $(A_{CC}^u + A_{\text{pen}}^{ut})$, and \mathcal{C} contains a strong phase. The amplitude for $\overline{B}_d^0 \rightarrow \pi^+\pi^-$ can be obtained from Eq. (3) by changing the sign of γ :

$$A(\overline{B}_d^0 \rightarrow \pi^+\pi^-) = \mathcal{C}(e^{-i\gamma} - de^{i\theta}). \quad (5)$$

There are both direct and mixing-induced CP asymmetries in $B_d^0(t) \rightarrow \pi^+\pi^-$. Defining

$$\mathcal{A}^{+-}(t) = \frac{\Gamma(B_d^0(t) \rightarrow \pi^+\pi^-) - \Gamma(\overline{B}_d^0(t) \rightarrow \pi^+\pi^-)}{\Gamma(B_d^0(t) \rightarrow \pi^+\pi^-) + \Gamma(\overline{B}_d^0(t) \rightarrow \pi^+\pi^-)} \\ = \mathcal{A}_{\text{dir}} \cos \Delta Mt + \mathcal{A}_{\text{mix}} \sin \Delta Mt, \quad (6)$$

we have

$$\mathcal{A}_{\text{dir}} = -\frac{2d \sin \theta \sin \gamma}{1 - 2d \cos \theta \cos \gamma + d^2}, \quad (7) \\ \mathcal{A}_{\text{mix}} = \frac{\sin(\phi_d + 2\gamma) - 2d \cos \theta \sin(\phi_d + \gamma) + d^2 \sin \phi_d}{1 - 2d \cos \theta \cos \gamma + d^2},$$

where ϕ_d is the phase of $B_d^0 - \overline{B}_d^0$ mixing.

The decay $B_d^0 \rightarrow \pi^+\pi^-$ is related to $B_s^0 \rightarrow K^+K^-$ by flavor SU(3). That is, we can write [7]

$$A(B_s^0 \rightarrow K^+K^-) = \left| \frac{V_{us}}{V_{ud}} \right| \mathcal{C}' \left(e^{i\gamma} + \left| \frac{V_{cs}V_{ud}}{V_{us}V_{cd}} \right| d' e^{i\theta'} \right), \quad (8)$$

where

$$\mathcal{C}' \equiv |V_{ub}^*V_{ud}|(A_{CC}^{u'} + A_{\text{pen}}^{u't}), \\ d' e^{i\theta'} \equiv \frac{1}{R_b} \left(\frac{A_{\text{pen}}^{c't}}{A_{CC}^{u'} + A_{\text{pen}}^{u't}} \right). \quad (9)$$

In the SU(3) limit, we have

$$\mathcal{C} = \mathcal{C}', \quad de^{i\theta} = d' e^{i\theta'}. \quad (10)$$

Thus, observables in the decay $B_s^0 \rightarrow K^+K^-$ are related to observables in $B^0 \rightarrow \pi^+\pi^-$. (Of course, SU(3)-breaking effects must also be taken into account. We do this below.)

We now define the ratio of BR's for $B_s^0 \rightarrow K^+K^-$ and $B_d^0 \rightarrow \pi^+\pi^-$:

$$R_d^s \equiv \frac{\langle BR(B_s \rightarrow K^+K^-) \rangle}{\langle BR(B_d \rightarrow \pi^+\pi^-) \rangle}, \quad (11)$$

where the symbol $\langle \dots \rangle$ indicates an average over B^0 and \overline{B}^0 decays. In terms of theoretical parameters, this ratio is given by

$$R_d^s = \frac{1}{\epsilon} \left| \frac{\mathcal{C}'}{\mathcal{C}} \right|^2 \frac{\epsilon^2 + 2\epsilon d' \cos \theta' \cos \gamma + d'^2}{1 - 2d \cos \theta \cos \gamma + d^2} f_{PS}. \quad (12)$$

where $\epsilon = \lambda^2/(1 - \lambda^2)$ and $\lambda = 0.22$ is the Cabibbo angle. The quantity

$$f_{PS} = \frac{M_{Bd}}{M_{Bs}} \times \frac{\tau_{Bs}}{\tau_{Bd}} \times \frac{\phi(M_K/M_{Bs}, M_K/M_{Bs})}{\phi(M_\pi/M_{Bd}, M_\pi/M_{Bd})} \quad (13)$$

is a (known) phase-space factor (see [7, 10]), which takes value $f_{PS} = 0.92$. (The experimental quantity R_d^s is related to the theoretical quantity H of Ref. [7].)

In the SU(3) limit, the three observables \mathcal{A}_{dir} , \mathcal{A}_{mix} and R_d^s all depend on the four theoretical parameters d , θ , ϕ_d and γ . However, ϕ_d has been measured through CP violation in $B_d^0(t) \rightarrow J/\psi K_s$ and, assuming the SM, we can take the value of γ from independent measurements. Then knowledge of two measurements allows us to *predict* the third. We can then compare this prediction with the experimental measurement to see if it is consistent. (Equivalently, we can solve for d , θ and γ using the three observables. We can then check for consistency by comparing the value of γ with that obtained elsewhere.)

Note that, if an inconsistency is found, this analysis does not pinpoint the origin of the physics beyond the SM. There are several places in which this new physics could enter: the extractions of ϕ_d or γ , or the amplitudes for $B^0 \rightarrow \pi\pi$ or $B_s^0 \rightarrow K^+K^-$. If a discrepancy is found, further experimental tests will be necessary to identify the new physics.

It is possible to explicitly write R_d^s in terms of \mathcal{A}_{dir} and \mathcal{A}_{mix} [10], but the analytic expression is not terribly illuminating. It is better to use figures to give the reader

a sense of what the relation between \mathcal{A}_{dir} , \mathcal{A}_{mix} and R_d^s looks like.

We first assume perfect SU(3) symmetry, with one exception. The ratio $|\mathcal{C}'/\mathcal{C}|$ has recently been calculated using QCD sum rules [13]:

$$\left| \frac{\mathcal{C}'}{\mathcal{C}} \right| = 1.76_{-0.17}^{+0.15}. \quad (14)$$

We take $|\mathcal{C}'/\mathcal{C}| = 1.76$ (with no error). The measurement of CP violation in $B_d^0(t) \rightarrow J/\psi K_S$ gives $\sin \phi_d = 0.73 \pm 0.05$ [12]. We take $\phi_d = 2\beta = 47^\circ$. (If $\phi_d = 133^\circ$ is taken, this would already be evidence for physics beyond the SM [14].) We also assume $\gamma = 65^\circ$, which is the value preferred by independent measurements (ϵ_K , V_{cb} , $|V_{ub}/V_{cb}|$, etc.) [15].

In Fig. 1a we present the (correlated) allowed values of R_d^s and \mathcal{A}_{dir} , for various values of \mathcal{A}_{mix} . Fig. 1b is similar, but with $\mathcal{A}_{dir} \leftrightarrow \mathcal{A}_{mix}$. In both cases, the values of the CP asymmetries respect [16]

$$\mathcal{A}_{dir}^2 + \mathcal{A}_{mix}^2 \leq 1. \quad (15)$$

From these figures, one sees that the equation relating \mathcal{A}_{dir} , \mathcal{A}_{mix} and R_d^s is independent of the sign of \mathcal{A}_{dir} , but not of \mathcal{A}_{mix} . Note also that this is a bi-value relation: for given values of \mathcal{A}_{dir} and \mathcal{A}_{mix} , there are two possibilities for R_d^s . This will be important when we add errors below. Finally, in Fig. 1c, we show the (correlated) allowed values of \mathcal{A}_{dir} and \mathcal{A}_{mix} , for various values of R_d^s .

Of course, there are errors on the input value of γ . We take $\gamma = (65 \pm 7)^\circ$ [15]. (However, we still assume that $2\beta = 47^\circ$, with no error.) We also include the error on the SU(3)-breaking quantity $|\mathcal{C}'/\mathcal{C}|$ [Eq. (14)]. There is also SU(3) breaking in comparing d and d' , and θ and θ' . We assume $d'/d = 1.0 \pm 0.2$, and $\theta' - \theta = 0^\circ \pm 40^\circ$ [17]. Normally, theoretical errors imply that the true value lies somewhere in the “ 1σ ” range. Thus, in our numerical analysis, we allow the various quantities to take any values in the following ranges: $58^\circ \leq \gamma \leq 72^\circ$, $1.49 \leq \mathcal{C}'/\mathcal{C} \leq 1.91$, $0.8 \leq d'/d \leq 1.2$, $-40^\circ \leq \theta' - \theta \leq 40^\circ$.

When these uncertainties are included, the \mathcal{A}_{dir} – \mathcal{A}_{mix} – R_d^s relation shown in Figs. 1a–1c gets smeared out. In Fig. 2, we present the allowed R_d^s – \mathcal{A}_{dir} region for three values of \mathcal{A}_{mix} : 0.1 (area inside the dashed line), 0.5 (dotted line) and 0.9 (solid line). For simplicity we consider only $\mathcal{A}_{dir} < 0$, so this plot can be thought of as the left half of Fig. 1a for the case where uncertainties are included in the analysis. From this plot, we see that, due to the theoretical error, the curves of Fig. 1a become wide regions. (For $\mathcal{A}_{mix} = 0.1$ and 0.5, there is still an area of R_d^s – \mathcal{A}_{dir} parameter space in the center of the region which is not allowed; for $\mathcal{A}_{mix} = 0.9$, there is no such area.)

Up to now, the discussion has been purely theoretical. However, experimental data is presently available

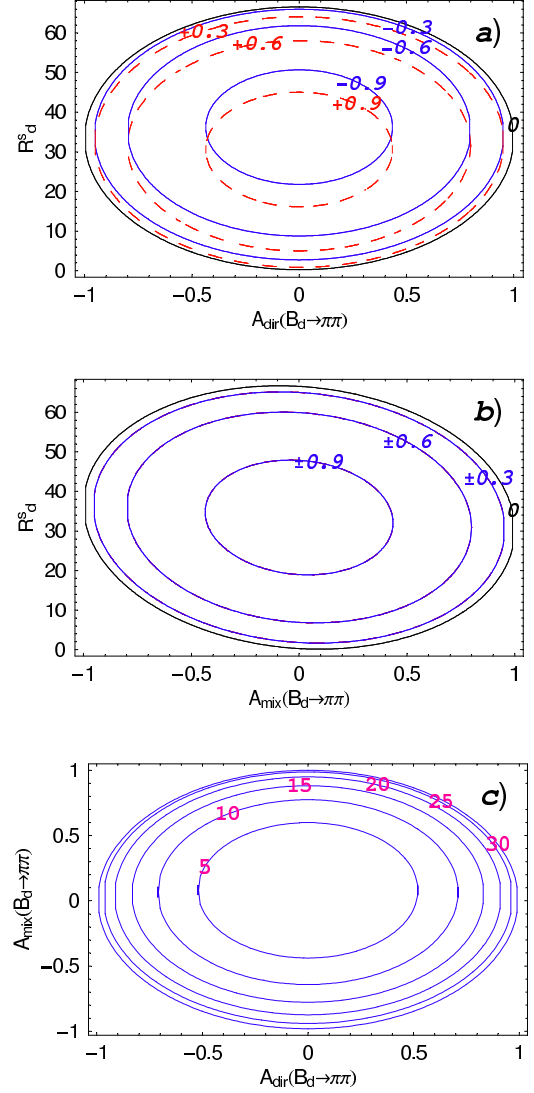


FIG. 1: The (correlated) allowed values of a) R_d^s and \mathcal{A}_{dir} , b) R_d^s and \mathcal{A}_{mix} , c) \mathcal{A}_{dir} and \mathcal{A}_{mix} in the SU(3) limit (except for $|\mathcal{C}'/\mathcal{C}|$). The values assumed for the third observable, a) \mathcal{A}_{mix} , b) \mathcal{A}_{dir} and c) R_d^s , are shown on the figures.

for \mathcal{A}_{dir} , \mathcal{A}_{mix} and R_d^s . For the $B_d^0 \rightarrow \pi^+\pi^-$ CP asymmetries, we have

$$\begin{aligned} \mathcal{A}_{dir} &= \begin{cases} -0.19 \pm 0.19 \pm 0.05 & \text{BaBar [18],} \\ -0.58 \pm 0.15 \pm 0.07 & \text{Belle [19].} \end{cases} \\ \mathcal{A}_{mix} &= \begin{cases} +0.40 \pm 0.22 \pm 0.03 & \text{BaBar [18],} \\ +1.00 \pm 0.21 \pm 0.07 & \text{Belle [19].} \end{cases} \end{aligned} \quad (16)$$

For the branching ratios, CDF recently reported [20]

$$\left(\frac{f_d}{f_s} \right) \frac{BR(B^0 \rightarrow \pi^+\pi^-)}{BR(B_s^0 \rightarrow K^+K^-)} = 0.35 \pm 0.18. \quad (17)$$

Taking $f_s/f_d = 0.27 \pm 0.04$ [12], we find

$$R_d^s = 10.6 \pm 5.7. \quad (18)$$

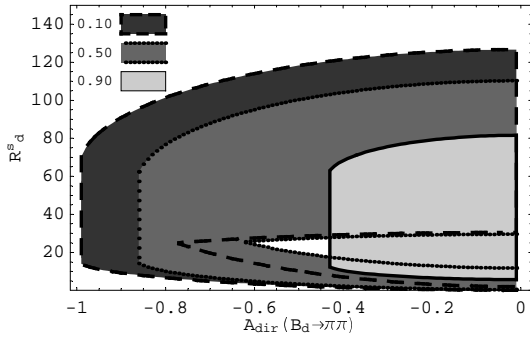


FIG. 2: The (correlated) allowed values of R_d^s and \mathcal{A}_{dir} for three values of \mathcal{A}_{mix} . We take the experimental and theoretical uncertainties into account: $58^\circ \leq \gamma \leq 72^\circ$, $1.49 \leq \mathcal{C}'/\mathcal{C} \leq 1.91$, $0.8 \leq d'/d \leq 1.2$, $-40^\circ \leq \theta' - \theta \leq 40^\circ$. For $\mathcal{A}_{mix} = 0.1, 0.5$ and 0.9 , the allowed R_d^s - \mathcal{A}_{dir} regions are, respectively, inside the dashed, dotted and solid lines.

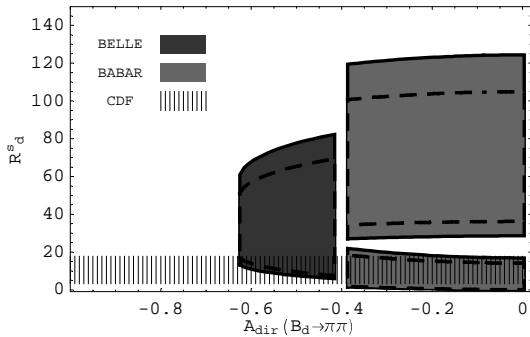


FIG. 3: The allowed values of R_d^s , including all theoretical uncertainties, as derived from measurements of \mathcal{A}_{dir} and \mathcal{A}_{mix} [Eq.(16)]. The Belle and BaBar data are treated separately, and the CP asymmetries are allowed to vary within their $\pm 1\sigma$ ranges. The CDF measurement of R_d^s [Eq.(18)] is superimposed (straight lines). The internal dashed line corresponds to the case where one has smaller SU(3) breaking, $0.9 \leq d'/d \leq 1.1$.

We can now compare the value of R_d^s implied by the measurements of the CP asymmetries [Eq. (16)] with that measured directly [Eq. (18)]. A discrepancy would signal the presence of new physics.

The current situation is shown in Fig. 3. We treat separately the Belle and BaBar measurements of the CP asymmetries [Eq.(16)]. We allow each of \mathcal{A}_{dir} and \mathcal{A}_{mix} to take values in their $\pm 1\sigma$ ranges. Including all theoretical uncertainties, this yields a range of allowed values for R_d^s . Note that the BaBar region is quite a bit bigger than that of Belle. This is because a large part of the Belle \mathcal{A}_{dir} - \mathcal{A}_{mix} parameter space is already ruled out, having violated the constraint of Eq. (15). Superimposed on this is the CDF result for R_d^s [Eq.(18)], also given for $\pm 1\sigma$. (We also show the case where the SU(3)-breaking effect is smaller than expected, $0.9 \leq d'/d \leq 1.1$, but this does not change things much.)

It is clear from this figure that, at present, there is no

discrepancy – the measured value of R_d^s overlaps with the BaBar and Belle regions. That is, the values of R_d^s predicted by measurements of the CP asymmetries include those of Eq. (18). On the other hand, the experimental errors are still very large. As these errors get reduced, this analysis will become increasingly useful as a method of searching for physics beyond the SM.

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